

Multiple Access Capacity Trade-offs for a Ka-Band Personal Access Satellite System

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ABSTRACT

System capacity is critical to the economic viability of a personal satellite communication system. Ka-band has significant potential to support a high-capacity multiple access system because of the availability of bandwidth. System design tradeoffs are performed and multiple access schemes compared with the design goal of achieving highest capacity and efficiency. Conclusions regarding the efficacy of the different schemes and the achievable capacities are given.

1.0 INTRODUCTION

The telecommunications infrastructure of the 21st Century will very likely be characterized by a diversity of services and a choice of media. In anticipation of the future needs in communications, the Jet Propulsion Laboratory (JPL) is exploring the potential and feasibility of a Personal Access Satellite System (PASS) which is intended to offer the user freedom of access and mobility [1,2].

The telecommunications industry of the future will undoubtedly witness fierce competition. The different systems will have to provide their benefits to the users in a cost-effective and efficient manner. Crucial to the economic viability of a satellite communication system targeted to the individual user is competitive and affordable user equipment. The importance of the reduction in cost achieved through the economies of scale cannot be over-emphasized. One of the primary reasons for selecting Ka-band for PASS is the availability of a considerable amount of bandwidth, easily an order of magnitude more than at L-band or UHF. This, in a successful system design, should translate into proportionally larger capacities, and in turn would translate into lower costs.

This paper addresses the issue of system capacity. Different multiple access scheme combinations are considered and compared. Tradeoffs of system parameters are performed to achieve highest capacity (in number of channels) and optimize efficiency (in channels/Hz). The implications of the results and comparisons are explained and conclusions regarding the efficacy of the different schemes are given.

2.0 SYSTEM PARAMETERS

The design of a PASS architecture is an intricate process that involves a multitude of factors. A first set of design parameters includes satellite RF power, overall system bandwidth, link performance specification, coding gains, voice activity, and ultimately, overall system capacity. Another set of factors that could be considered include number of beams on each satellite link, user EIRP, user receive G/T, basic terminal types and associated data rates. This latter set of parameters is tied directly or indirectly to the capabilities of the user terminal. Since those capabilities have evolved through a study of soon-to-be-available or projected Ka-band technologies [2], it is felt that design optimization should, at least at this stage, focus only on the former group of parameters. In addition to avoiding a radical impact on PASS, this also renders the multiple access design problem tractable.

In 1988 a system architecture utilizing a hybrid Time Division Multiple Access (TDMA)/ Frequency Division Multiple Access (FDMA) was investigated [2,3]. The architecture called for TDMA in the forward direction (from Suppliers to Users), and FDMA in the return direction (from Users to Suppliers). An alternative architecture employing

Random Access Code Division Multiple Access (CDMA) was studied in 1989 [4]. The CDMA schemes considered in [4], as well as here, employ direct-sequence spreading, and could therefore be referred to also as Spread Spectrum Multiple Access (SSMA). Direct-spreading provides added benefits in the personal or mobile environment including multipath rejection and position determination.

Based on the chosen design approach, a set of basic system architecture constraints is common to all of the access schemes considered. These include the use of the satellite as a bent-pipe repeater, with a CONUS beam for the satellite/supplier side, a multi-beam antenna on the satellite/user side, and with a fixed set of parameters such as gain and G/T. The basic user terminal and supplier station also have pre-selected specifications. Table 1 contains a summary of the key system parameters that have been kept fixed. On the satellite/user links, frequency re-use is employed on the 142 beams so that only 9 frequency bands are used in covering CONUS.

Table 1. Summary of Pre-Set PASS Parameters

<u>GENERAL</u>	
OPERATING FREQUENCIES	
UPLINK	30 GHZ
DOWNLINK	20 GHZ
COVERAGE CONCEPT	
SAT/SUPPLIERS	CONUS BEAM
SAT/USERS	SPOTBEAMS
<u>BASIC PERSONAL TERMINAL</u>	
G/T	-9.0 DB/K
EIRP	16.8 DBW
BASIC DATA RATE	4800 BPS
<u>SATELLITE</u>	
SPOTBEAM ANTENNA	
NUMBER OF SPOTBEAMS	142
ANTENNA GAIN	52.5 DBI
SYSTEM G/T	23.4 DB/K
AVERAGE EIRP/BEAM	55 DBW
CONUS ANTENNA	
ANTENNA GAIN	27.0 DB
SYSTEM G/T	-1.2 DB/K
EIRP	39 DBW
<u>SUPPLIER STATION</u>	
G/T	60.7 DB/K
EIRP	30.3 DB

3.0 LINK CHARACTERIZATION

The factors of satellite RF power, system bandwidth, link performance/coding performance and system capacity are all tied together through a set of link budget equations, complimented with bandwidth and capacity computations. Two link budget equations, one for the forward and one for the return, are needed for each multiple access scheme. Each pair of forward and return budgets is tied together through the key constraint of limited overall satellite RF power. Occasionally, the satellite power used on the two link directions could be traded effectively to increase overall capacity, or to balance the forward and return capacities. Unfortunately, in many circumstances the gains achieved are limited due to the constraints placed on the system.

A simple approach to understand the various situations existing on the different links is to consider the basic equation relating the received bit signal to noise ratio to the down-link and up-link carrier to noise ratios, and in the case of CDMA, to the added mutual interference. This equation can be written as

$$\left\{ \frac{E_b}{N_0} \right\}^{-1} = \left\{ \frac{P_{rd}}{R_b N_0} \right\}^{-1} + \left\{ \frac{P_{ru}}{R_b N_{0u}} \right\}^{-1} L_d + \left\{ \frac{R_c}{(M-1)R_b} \right\}^{-1} \quad (1)$$

where E_b denotes the received energy per bit, N_0 is the one-sided thermal noise power spectral density. P_r is the received signal power with the second subscript d or u denoting down-link or up-link (at the satellite), respectively. L_d is the loss that the transponded up-link signal plus noise experience by going through the satellite and the down-link environment. R_c is the chip rate, R_b is the bit rate, and $(M-1)$ are the simultaneous interfering users. For FDMA the third term is simply dropped.

When the first term in the right hand side of (1) dominates, link performance is limited by the thermal noise on the down-link. Similarly, when the second term dominates, performance is limited by up-link thermal noise. Finally, in a CDMA system, if the third term dominates, link operation is mutual interference limited. The inverse of each term (i.e., the quantity between parentheses) can be regarded as an effective signal to noise ratio (SNR) for either the down-link, up-link, or mutual interference. Naturally, the lowest SNR drives the attainable E_b/N_0 . An "efficient" system design generally requires more or less equal contributions from the three terms. In a system such as PASS this is rarely

achievable due to the constraint on the overall RF power. This power is not only used to amplify the uplink signal but also the uplink noise, which can become significant in a wide band system. Although this "power robbing" type of effect is not explicitly shown in (1), it is manifested in a drop in P_{Tq} (an increase in the first term of (1)) when bandwidth is increased to accommodate a higher chip rate; so an attempt to reduce the third term results in increasing the first. Consequently, an "optimal" chip rate can be found to maximize link performance under the given power constraints.

4.0 PERFORMANCE TRADEOFFS

The strawman design of PASS described in [2,3] has utilized a 6000 lb-class satellite providing 410 watts of RF power. This satellite along with a somewhat larger satellite with roughly 25% more RF transmit power capability are selected for the tradeoff. Different satellite powers are considered since system performance in severely noise limited conditions inherently favors FDMA. In fact, it will become clear from the discussions to follow that a satellite sized for an FDMA architecture does not generally support an optimal CDMA design. This can be intuitively derived from (1) since there is one more term that the system/satellite designer has to contend with in CDMA.

In the tradeoffs link BER specification is taken to be either 10^{-3} or 10^{-5} . The usual performance for voice channels is 10^{-3} . However, it is possible that a more stringent 10^{-5} requirement be placed on data links. The E_b/N_0 needed is determined by the BER and the choice of a suitable coding scheme consistent with either the FDMA, TDMA or CDMA approach.

One of the inherent advantages of CDMA is that coding gain can be achieved without further expanding the bandwidth. Consequently, powerful codes can be applied without that usual penalty. Convolutional codes of rates $R=1/2$ and $R=1/3$ and constraint lengths $K=7$ and $K=9$ are considered. Lowering the code rate from $1/2$ to $1/3$ with $K=7$ is achieved at only a minor cost/complexity increment to the user terminal. The more powerful code with $R=1/3$ and $K=9$ is included for its lower E_b/N_0 requirement of about 1.5 dB for a BER of 10^{-3} in additive white Gaussian noise. As will be seen, CDMA capacity is quite sensitive to this E_b/N_0 requirement. A novel set of codes known as super-orthogonal codes could be selected to obtain this 1.5 dB performance [5]. These codes have a rate of

$2^{-(K-2)}$, and in a spread spectrum system the code rate is taken to be the ratio of the bit to chip rates. Reportedly [5], reasonable K values for such a system are 10 to 12. The impact of having the symbol rate equal to the chip rate on the robustness of CDMA needs a close look; however, the main advantage of this coding scheme is the reduced E_b/N_0 requirement. Hence, for the purposes of our tradeoffs the $R=1/3$, $K=9$ code and the super-orthogonal codes are generally equivalent.

For FDMA both rate $1/2$ and $1/3$ codes with $K=7$ and 9 are considered. Super-orthogonal codes are not applicable since they would expand the bandwidth by at least 256 times.

The bandwidth requirements computed in what follows are based on some assumptions. The baseline beam and frequency plan mentioned above, and described in detail in [2,3,4], is assumed. For CDMA a channel bandwidth is taken to be twice the chip rate. For FDMA, twice the symbol rate is used plus 5 kHz of guard band is allowed. No allowance is considered for intermodulation products avoidance in either scheme since the satellite HPA is assumed to operate in the linear region. This is necessitated by the baseline multiple beam/FDM architecture common to either the FDMA or CDMA strategies.

4.1 Lower Power Satellite Trades

The forward and return link capacities for the 410 W satellite (in terms of number of 4800 BPS users) are given in Table 2. A host of coding choices and service types (voice or data) is provided.

We start by observing that under the given power and bandwidth constraints the CDMA/CDMA approach cannot compete with either FDMA/TDMA or CDMA/TDMA. A close examination of the link budgets and the applicable terms in (1) reveals certain inherent limitations in the design problem. For the CDMA/CDMA entries number 9 or 10 of Table 2, the down/up/mutual SNR's (R.H.S. of (1)) are 11/10/20 for the return and 5.5/96/21.7 for the forward, where the numbers are in ratio. The optimal satellite power allocation was found to be 375/35 for the return/forward directions. This clearly shows that system performance is severely thermal noise limited on the forward down-link; which is indeed the segment that requires most of the satellite power. Numbers for the FDMA/TDMA baseline [2,3] (corresponding to entry 1 in the table) are 10/22 for the down/up

4.2 Higher Power Satellite Trades

return and 7.6/93.7 for the down/up forward. Obviously, the baseline design is also power limited on the forward down-link. This bottleneck on the forward down-link is further exacerbated in the CDMA design, particularly when both directions use CDMA. This is because some satellite power has to be set aside to combat mutual interference and to amplify a wider up-link noise band; the forward down-link becomes even more power starved.

For CDMA to be a viable candidate the solutions involve one or more of the following: 1) use CDMA only on the return link and TDMA on the forward, this results in bandwidth and power savings by eliminating the spreading on the forward link if random access is not needed; 2) increase the satellite power to enable the multiple access needs of CDMA while not aggravating the thermal noise bottleneck in the forward down-link; 3) reduce the received power requirements at the user such as with the use of $R=1/3$, $K=9$ or super-orthogonal codes.

The comparison of FDMA/TDMA with CDMA/TDMA is also given in Table 2 for the 410 W satellite. For data links FDMA is clearly the proper choice based on the number of channels and the required bandwidth. This is seen by comparing entries 1 and 4 versus 11 for a BER requirement of 10^{-5} , and 5 versus 12 for a BER of 10^{-3} . Roughly the same data channel capacity is obtained at half the bandwidth (compare entries 5 and 12). Because of the voice activity factor (0.35) CDMA excels in a voice dominated system; as channels are added the bandwidth requirement does not change-- whereas it increases substantially for FDMA (compared to data only). Entries 3 and 6 for FDMA and 13 for CDMA clearly demonstrate this fact. A higher number of voice channels per Hz is obtained with CDMA, even without the more powerful codes requiring only 1.5 dB E_b/N_0 . Going to $R=1/3$, $K=9$ or super-orthogonal codes (entries 7, 14 and 15) CDMA's advantage in channels/Hz increases further.

An interesting tradeoff can be seen in entries 15a,b. The power savings realized on the return link can be transferred to the forward direction to boost its capacity. Because the forward link is so power thirsty, the gains obtained in this manner are not large. Alternately, the capacity of the forward can be left fixed, and dramatic gains shown on the return (entry 15.a). This will be illustrated further in the case of a 520 W satellite.

The situation with 520 W RF power on the satellite is quite interesting because it ameliorates the power bottleneck on the forward down-link. Steps similar to above are followed to optimize the RF power distribution between the forward and return directions and to optimize the chip rate and bandwidth. The results are shown in Table 3.

The first observation is that increased RF satellite capability notwithstanding, FDMA is still the better choice for data. The situation becomes quite different for a system dominated by voice users (entries 3 and 8 for example). Roughly three times as many users as the all data case can be supported with CDMA at no extra cost. The equivalent increase in channels for FDMA is achieved at a three fold increase in bandwidth. Table 3, entries 3 and 8, give the net results for the same total bandwidth of 285 MHz. The results evince a slightly higher CDMA capacity in the forward direction and a 16% advantage for the return.

It is interesting to note here that power limitations on the forward link persist (SNR break-ups for entry 8 are 4.4/76.7 forward and 25.5/10/10.1 return). Increasing the satellite power beyond 520 Watt would predominantly improve the forward capacity. As mentioned earlier, an alternate approach is the use of a more powerful code on the CDMA return and transferring some power to the forward link. This is achieved with either the $R=1/3$, $K=9$ or the super-orthogonal codes as demonstrated in entries 9 and 10. In particular, entry 9.a when compared to entry 3 shows CDMA capacity advantages of 8% on the forward and 16% on the return, together with an 8% savings in total bandwidth. Alternately, the forward capacity can be maintained as in entry 8 and all of the performance savings used on the return to realize a 43% advantage over FDMA (entry 9.b versus 3). In fairness it should also be mentioned that super-orthogonal decoding is likely to be more complex than typical Viterbi decoding.

The final step in the CDMA vs. FDMA comparison centers around allowing a higher overall PASS system bandwidth. The bandwidth is allowed to exceed the "magical number" of 285 used above. This comparison is relevant here since there is enough satellite power to use the extra bandwidth. As the code rate is reduced to 1/3 in FDMA the bandwidth leaps from 285 to 468 or 631 MHz, depending on the code used, to support the

additional voice channels now feasible. For CDMA, either $R=1/3$, $K=9$ or super-orthogonal codes with $K=11$ are used. A comparison of entries 10 and 11 for CDMA with 4 and 5 for FDMA demonstrates a considerably higher efficiency in channels/Hz for CDMA.

5.0 CONCLUSIONS

The following conclusions can be drawn in the context of the above results and discussions.

- o Due to power limitations on the satellite, and for bandwidth efficiency considerations as well, CDMA should not be used on the forward link. TDMA should be used.
- o For a system dominated by data users, FDMA is superior based on lower bandwidth requirements. FDMA in general can support a higher number of channels if performance is very power limited (e.g., a thermal noise limited performance on the forward down-link if a 10^{-5} data BER is the predominant requirement in the system).
- o For a system dominated by voice users CDMA is superior; it generally requires less bandwidth than FDMA, or can support a higher number of users for a given bandwidth.
- o The increases in capacity with the lowering of the user E_b/N_0 requirement is more significant for CDMA than for FDMA. Alternately, increased satellite power is more advantageous for CDMA in the sense that it can be used more efficiently than in FDMA.
- o Since future trends are for lower E_b/N_0 requirements and higher satellite RF powers, CDMA appears to be a stronger candidate for a state of the art system (provided that a significant proportion of the traffic is voice).
- o Overall capacities that are half to a full order of magnitude higher than at L-band [6] are achievable. However, a concomitant increase in overall system bandwidth of about an order of

magnitude is experienced. This bandwidth requirement is one of the primary reasons for migrating to the uncrowded Ka-band region.

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TABLE 2. COMPARISONS OF PASS CAPACITIES FOR DIFFERENT MULTIPLE ACCESS DESIGNS FOR A SATELLITE WITH 410 W TOTAL RF POWER
 NOTE: VOICE ACTIVITY FACTOR (VOX) FOR VOICE CHANNELS TAKEN TO BE 0.35

ENTRY #	ACCESS SCHEMES	LINK PARAMETERS BER	EB/NO dB (CONVOLUTIONAL)	CODING	SERVICE TYPE	CAPACITY (# CHANNELS) RETURN	FORWARD	UP-LINK	BANDWIDTH DN-LINK	(MHz) TOTAL	SAT POWER, W SPLIT (F/R)	COMMENTS
1	FDMA (RET) / TDMA (FWD)	1.00E-05	4.5	R=1/2, K=7	DATA	2000	2036	27.7	27.3	55	390/20	
2	"	1.00E-03	3	R=1/2, K=7	DATA	2825	2875	39.1	38.6	77.7	390/20	
3	"	1.00E-03	3	R=1/2, K=7	VOICE	8072	8216	111.8	110.3	222.1	390/20	
4	"	1.00E-05	4	R=1/3, K=7	DATA	2244	2284	43.4	42.8	86.2	390/20	
5	"	1.00E-03	2.3	R=1/3, K=7	DATA	3319	3378	64	63	127	390/20	
6	"	1.00E-03	2.3	R=1/3, K=7	VOICE	9483	9653	183.4	181	364.4	390/20	
7	"	1.00E-03	1.5	R=1/3, K=9	VOICE	11401	11605	220	218	438	390/20	
.....												
8	CDMA (RET) / CDMA (FWD)	1.00E-05	4	R=1/3, K=7	DATA	852	1278	150	100	250	350/60	
9	"	1.00E-03	2.3	R=1/3, K=7	DATA	2414	2272	225	225	450	375/35	
10	"	1.00E-03	2.3	R=1/3, K=7	VOICE	6897	6491	225	225	450	375/35	
.....												
11	CDMA (RET) / TDMA (FWD)	1.00E-05	4	R=1/3, K=7	DATA	1704	1775	50.9	203	253.9	295/115	Rc=1.40625M; Rb=60K
12	"	1.00E-03	2.3	R=1/3, K=7	DATA	3550	2958	65.1	183	248.1	335/75	Rc=1.25M; Rb=100k
13	"	1.00E-03	2.3	R=1/3, K=7	VOICE	10143	8452	65.1	183	248.1	335/75	Rc=1.25M; Rb=100k
14	"	1.00E-03	1.5 (R) / 2.3 (F)	SUP.-ORTH(K=10) / R=1/3, K=7	VOICE	10142	9331	69.1	180	249.1	375/35	Rc=1.228800M Rb=110.4k
15.a	"	1.00E-03	1.5	R=1/3, K=9	VOICE	10142	11072	78.3	185	263.3	375/35	Rc=1.25M; Rb=131k
15.b	"	1.00E-03	1.5	R=1/3, K=9	VOICE	16228	9720	76	219	295	330/80	Rc=1.5M; Rb=115k

TABLE 3. COMPARISONS OF PASS CAPACITIES FOR DIFFERENT MULTIPLE ACCESS DESIGNS FOR A SATELLITE WITH 520 W TOTAL RF POWER
 NOTE: VOICE ACTIVITY FACTOR (VOX) FOR VOICE CHANNELS TAKEN TO BE 0.35

ENTRY #	ACCESS SCHEMES	LINK PARAMETERS BER	E _b /N ₀ dB	CODING (CONVOLUTIONAL)	SERVICE TYPE	CAPACITY (# CHANNELS) RETURN	UP-LINK FORWARD	BANDWIDTH DN-LINK	(MHz) TOTAL	SAT POWER, W SPLIT (F/R)	COMMENTS	
1	FDMA (RET) / TDMA (FWD)	1.00E-05	4.5	R=1/2, K=7	DATA	2600	2585	35.3	35.4	70.7	494/26	
2	"	1.00E-03	3	R=1/2, K=7	DATA	3673	3652	49.8	50	99.8	494/26	
3	"	1.00E-03	3	R=1/2, K=7	VOICE	10493	10433	142.3	143	285.3	494/26	
4	"	1.00E-03	2.3	R=1/3, K=7	VOICE	12328	12258	233.6	234.6	468.2	494/26	
5	"	1.00E-03	1.5	R=1/3, K=9	VOICE	16630	16536	315	316.5	631.5	494/26	
6	CDMA (RET) / TDMA (FWD)	1.00E-05	4	R=1/3, K=7	DATA	2070	2130	58	226	284	350/170	Rc=1.5625M (R) Rb=70k (F)
7	"	1.00E-03	2.3	R=1/3, K=7	DATA	4260	3698	78.6	206.4	285	425/95	Rc=1.40625M; RB=125k (R) (F)
8	"	1.00E-03	2.3	R=1/3, K=7	VOICE	12171	10565	78.6	206.4	285	425/95	Rc=1.40625M; RB=125k
9.a	"	1.00E-03	1.5 (R) / 2.3 (F)	S. ORTH. (K=10) / R=1/3, K=7	VOICE	12171	11411	80	182	262	470/50	Rc=1.2288M; Rb=135k
9.b	"	1.00E-03	1.5 (R) / 2.3 (F)	S. ORTH. (K=10) / R=1/3, K=7	VOICE	15011	10565	75.4	181	256.4	425/95	Rc=1.2288M; Rb=125k
10.a	"	1.00E-03	1.5	R=1/3, K=9	VOICE	13794	13523	99.8	258.2	358	470/50	Rc=1.7578M; Rb=160k
10.b	"	1.00E-03	1.5	R=1/3, K=9	VOICE	19069	11411	85.1	225	310.1	390/130	Rc=1.5328M; Rb=135k
11	"	1.00E-03	1.5 (R) / 2.3 (F)	S. ORTH. (K=11) / R=1/3, K=7	VOICE	17851	11411	101.8	356.3	458.1	460/60	Rc=2.4576M; Rb=135k